

High-temperature spin polarization of high-mobility charge carriers in hybrid metal-semiconductor structures

Meilikhov E.Z., Farzetdinova R.M.

Kurchatov Institute, 123182 Moscow, Russia

We consider magnetic properties of the planar structure consisting of a ferromagnetic metal, diluted magnetic semiconductor and the quantum well (by the example of the hybrid heterostructure Fe–Ga(Mn)As–InGaAs). In the framework of the mean-field theory, there is the significant amplification of the ferromagnetism induced by the ferromagnetic metal (Fe) in the system of magnetic impurities (Mn) due to their indirect interaction via the conductivity channel in the quantum well. As a result, the high-temperature ferromagnetism arises leading to the spin polarization of charge carriers (holes) localized in the quantum well and preserving their high mobility.

Introduction

Among troublesome barriers on the way to the development of the semiconductor spintronics, there are two principal ones – the lack of semiconductor materials and structures which would be (i) ferromagnetic at high (room) temperature, and (ii) would possess high enough mobility of charge carriers. In this connection, there may be promising hybrid ferromagnetic metal/semiconductor structures whose magnetic properties are significantly determined by the high-temperature ferromagnetism of the constituent metal [1, 2], and heterostructures based on diluted magnetic semiconductors with removed doping and characterized by the high carrier mobility in the quasi-two-dimensional conductivity channel [3].

High-temperature magnetism in the semiconductor part of the first type structures is conditioned by inducing magnetic order in impurity atoms of the diluted magnetic semiconductor due to the proximity effect [1], however the mobility of polarized charge carriers (holes) is very low at that ($\sim 1\text{--}10 \text{ cm}^2/(\text{V}\cdot\text{s})$ [4]). To remedy this, one could spatially separate those atoms and holes to obtain the amplification of the above-mentioned seed magnetic order by means of the indirect interaction of impurity atoms through the tails of carriers' wave functions mainly localized in the quantum well. It has been experimentally shown that such a spatial separation results in a high carrier mobility ($\sim 10^3 \text{ cm}^2/(\text{V}\cdot\text{s})$ [5]), though obtained Curie temperatures (with no magnetic seed induced by the proximity effect) do not exceed 250 K [6].

In the present paper, we consider magnetic properties of hybrid heterostructures (of $\text{Fe–Ga}_{1-x}\text{Mn}_x\text{As–In}_y\text{Ga}_{1-y}\text{As}$ -type, cf. Fig. 1) where one could realize both mentioned principles. High-mobility charge carriers (holes) are concentrated in the two-dimensional quantum well appearing in the narrow-band gap non-magnetic semiconductor $\text{In}_y\text{Ga}_{1-y}\text{As}$ near its junction with the wide-band gap magnetic semiconductor $\text{Ga}_{1-x}\text{Mn}_x\text{As}$, whereas impurity atoms of the latter are magnetized by Fe atoms. Fe film, at such, is in the ferromagnetic single domain state being magnetized up to the saturation (along the unit vector ρ_0 parallel to the interface). Such a system, as we will show could combine magnetic order with the high carrier mobility over a wide range of temperatures.

Mean-field model

The magnetization of the diluted magnetic semiconductor (which is parallel to the interface due to the shape magnetic anisotropy) is significantly non-uniform along the growth axis z (cf. Fig. 1). It could be conveniently characterized by the local magnetization $-1 \leq j(h) \equiv M(h)/M_s \leq 1$, directed along the unit vector ρ_0 ($M(h)$ is the local magnetization at the distance h from the Fe/Ga_{1-x}Mn_x-interface plane, M_s is the saturation magnetization). In the framework of the mean-field theory it is defined by the equation

$$j(h) = B_S \left[-\frac{W(h)}{kT} \right], \quad (1)$$

where B_S is the Brillouin function for the spin S of Mn atoms,

$$W(h) = \sum_i w_{\text{Fe}}(\mathbf{R}_i) + \sum_k w_{\text{Mn}}(\mathbf{r}_k) \quad (2)$$

is the energy of the magnetic interaction of a given Mn atom with other parts of the structure. This energy is the sum of energies w_{Fe} and w_{Mn} of its pair interactions with individual Fe and Mn atoms, spaced at distances \mathbf{R}_i and \mathbf{r}_k from the specified Mn atom, respectively. Summation is performed over all Fe atoms (in the first sum) and all Mn atoms (in the second sum).

When calculating the first sum in (2), the interaction of Mn atoms will be considered being antiferromagnetic one [1] and corresponding effective magnetic field being also directed along the unit vector ρ_0 . Because considered Fe and Mn atoms are located in media characterized, in general, by different lengths of the exchange interaction, the result of that interaction is not merely the function of the distance R_i between those atoms. However, for not to complicate calculations with non-principal details we will proceed below from the following model spatial dependence

$$w_{\text{Fe}}(R_i) = -J_{\text{Fe}} \exp[-R_i/\ell_{\text{Fe}}] \rho_0 \cdot \mathbf{S}_i, \quad (3)$$

where J_{Fe} and ℓ_{Fe} are, correspondingly, the characteristic energy and length of the considered interaction for Mn atom with the spin \mathbf{S}_i . Putting the coordinate origin in the interface plane, we assume that Fe layer occupies the interval $-L_{\text{Fe}} < z < 0$, and the semiconductor film Ga(Mn)As takes up the range $0 < z < L_{\text{Mn}}$ (cf. Fig. 1). Then, in the continual approximation

$$\sum_i w_{\text{Fe}}(R_i) = -J_{\text{Fe}} S n_{\text{Fe}} \int_{z=-L_{\text{Fe}}}^0 \int_{\rho=0}^{\infty} \exp \left[-\sqrt{\rho^2 + (h-z)^2}/\ell_{\text{Fe}} \right] 2\pi \rho d\rho dz, \quad (4)$$

where n_{Fe} is the concentration of Fe atoms. From Eq. (4) it follows

$$\sum_i w_{\text{Fe}}(R_i) = -4\pi n_{\text{Fe}} \ell_{\text{Fe}}^3 S J_{\text{Fe}} F(h), \quad F(h) = e^{-h/\ell_{\text{Fe}}} \left[1 + \frac{h}{2\ell_{\text{Fe}}} - \left(1 + \frac{L_{\text{Fe}} + h}{2\ell_{\text{Fe}}} \right) e^{-L_{\text{Fe}}/\ell_{\text{Fe}}} \right]. \quad (5)$$

The calculation of the second sum in (2) should be preceded by the following comment. Presently, there is no full understanding the nature of the ferromagnetism in diluted magnetic semiconductors. Among mechanisms leading to the ferromagnetic ordering of magnetic impurities' spins they consider different types of their indirect interaction via mobile charge carriers: RKKY-exchange [7], kinematic exchange [8, 9], etc. [8]. In addition, there is the universal

Bloembergen-Rowland mechanism [10], that does not require the existence of charge carriers (or their high concentration resulting in the carrier degeneracy) and could be drawn for explaining ferromagnetism in the systems like Ga(Mn)As, Ga(Mn)N [11]. In this connection, we will use the RKKY mechanism as a *model* interaction (without insisting upon its universality for the considered systems).

In the *really two-dimensional* case, when magnetic impurities are situated in the plane of the two-dimensional gas of charge carriers, the energy of their RKKY interaction equals

$$w_{\text{Mn}}^0(\rho_k) = -J_{\text{Mn}}\phi(\rho_k)\mathbf{S}_0 \cdot \mathbf{S}_k, \quad (6)$$

where ρ_k is the distance between a given Mn atom (with the spin \mathbf{S}_0) and any one of other Mn atoms (with the spin \mathbf{S}_k). The characteristic interaction energy J_{Mn} and the function $\phi(r_{ik})$ define by the relationships [12]

$$J_{\text{Mn}} = \left(J_{pd}^2 \frac{m^* a_0^2}{4\pi\hbar^2} \right), \quad \phi(\rho_k) = (k_F a_0)^2 [J_0(k_F \rho_k) N_0(k_F \rho_k) + J_1(k_F \rho_k) N_1(k_F \rho_k)] e^{-\rho_k/\ell_{\text{Mn}}}, \quad (7)$$

where J_{pd} is the energy of *p-d* interaction, $k_F = (\pi N_s)^{1/2}$ is the Fermi wave number of carriers, J_n and N_n are Bessel functions (with $J_{\text{Mn}} \approx 0.1$ eV [13]), $a_0 \approx 6\text{\AA}$ is the side of GaAs cubic cell. The exponential factor in Eq. (7) takes into account the damping of the interaction (with the characteristic length ℓ_{Mn}) due to the scattering of carriers [14]. In the *bulk* diluted magnetic semiconductor $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ with the actual impurity concentration $x \approx 0.05$, the hole mobility is rather low: $\mu_h = 1-10 \text{ cm}^2/\text{V}\cdot\text{s}$ [4], that corresponds to their mean free path along the quantum well $\ell_0 \sim a_0$.

Those relations fall into the case when Mn atoms and charge carriers, providing their interaction, are placed together within the quasi-two-dimensional conductivity channel.

In our case, mobile charge carriers are localized in the quantum well being spatially separated from Mn atoms. The interaction of magnetic atoms occurs due to the leakage of the carrier wave function into the region of their arrangement. Then, as it has been shown in [3], the three-link chain of interactions works: (i) interaction of a given impurity i with the channel + (ii) transfer of the interaction along the quasi-two-dimensional channel + (iii) interaction of a removed impurity k with the channel. Each of them leads to the specific factor in the total expression for the interaction energy:

$$w_{\text{Mn}}(\rho_k, z_k) = w_{\text{Mn}}^0(\rho_k) \cdot \left[\frac{\psi_b^2(z_i)}{\psi_{\text{max}}^2} \right] \cdot \left[\frac{\langle \psi_a^2 \rangle}{\psi_{\text{max}}^2} \right] \cdot \left[\frac{\psi_b^2(z_k)}{\psi_{\text{max}}^2} \right]. \quad (8)$$

Here, ψ_{max} is the maximum value of the carrier wave function in the well (corresponding to the peak of their concentration in the quasi-two-dimensional channel), $\psi_b(z)$ is their wave function, leaking into the magnetic semiconductor, and $\langle \psi_a^2 \rangle$ is the average value of squared wave function in the well that could be found by means of the relation [3]

$$\langle \psi_a^2 \rangle = \frac{1}{\sqrt{3}} \left(\frac{1}{2a} \int_{L_{\text{Mn}}}^{\infty} \psi_a^2(z) dz \right), \quad (9)$$

where

$$a = \left\{ \int_{L_{\text{Mn}}}^{\infty} z^2 \psi_a^2(z) dz / \int_{L_{\text{Mn}}}^{\infty} \psi_a^2(z) dz - \left[\int_{L_{\text{Mn}}}^{\infty} z \psi_a^2(z) dz / \int_{L_{\text{Mn}}}^{\infty} \psi_a^2(z) dz \right]^2 \right\}^{1/2}$$

is the effective half-width of the wave function in the well.

Spatial separation of impurities and charge carriers in the considered structures leads, on the one hand, to weakening the indirect interaction, and results, on the other hand, in increasing the mean free path of carriers that promotes the strengthening of that interaction. If magnetic impurities are situated out of the well, the mean carrier free path ℓ increases[16] (comparing to its value ℓ_0 corresponding to the case when they are inside the well):

$$\ell_{\text{Mn}} = \ell_0 \frac{\langle \psi_a^2 \rangle}{\langle \psi_b^2 \rangle}, \quad (10)$$

where $\langle \psi_b^2 \rangle = (1/2\sqrt{3}b) \int_0^{L_{\text{Mn}}} \psi_b^2(z) dz$ is the averaged (over the impurity layer) value of the squared wave function with the effective half-width

$$b = \left\{ \int_0^{L_{\text{Mn}}} z^2 \psi_a^2(z) dz / \int_0^{L_{\text{Mn}}} \psi_a^2(z) dz - \left[\int_0^{L_{\text{Mn}}} z \psi_a^2(z) dz / \int_0^{L_{\text{Mn}}} \psi_a^2(z) dz \right]^2 \right\}^{1/2}.$$

The respective increase of the carrier mobility could be very significant. For instance, in [5] it has amounted to 2-3 orders of value that has allowed Shubnikov oscillations of the conductivity and quantum Hall effect in the two-dimensional channel of the single-well structure with the concentration of removed (from the channel) impurities $x \approx 0.05$.

Thus, the removed doping promotes increasing the carrier mobility and, as a consequence, leads to increasing the energy of indirect interaction of magnetic impurities.

Introducing the cylindrical coordinate system with the former origin of the z -axis and the radius-vector ρ , parallel to the interface plane, we will characterize the magnetic order arising in the system of impurities by the reduced magnetization $-1 < j = j(z, r) < 1$, which coincides with the impurity spin polarization degree. Neglecting the crystal and surface anisotropy, one notices that the shape anisotropy and the system symmetry result in that the local magnetization is everywhere directed along the plane of the impurity layer and depends on z only: $j = j(z)$.

In the continual approximation, the total energy of the indirect interaction of the impurity, located in the point $z = h$, $\rho = 0$, with all surrounding impurities equals

$$\begin{aligned} \sum_k w_{\text{Mn}}(\rho_k, z_k) &\approx \iint w_{\text{Mn}}(\rho, z) 2\pi \rho d\rho dz = \\ &= -2\pi n_{\text{Mn}} S^2 J_{\text{Mn}} \left[\frac{\langle \psi_a^2 \rangle}{\psi_{\text{max}}^2} \right] \left[\frac{\psi_b^2(h)}{\psi_{\text{max}}^2} \right] \int_{\rho_{\text{min}}}^{\infty} \phi(\rho) \rho d\rho \cdot \int_{z=0}^{L_{\text{Mn}}} \left[\frac{\psi_b^2(z)}{\psi_{\text{max}}^2} \right] j(z) dz, \end{aligned} \quad (11)$$

where it has been taken into account that the distance between impurities could not be smaller than the certain minimum distance, which for Mn atoms substituting Ga atoms in GaAs lattice equals $\rho_{\text{min}} = a_0/\sqrt{2}$.

Let us introduce the function

$$\Phi(k_F, \ell) = -\frac{\pi}{a_0^2} \int_{\rho_{\text{min}}}^{\infty} \phi(\rho) \rho d\rho, \quad (12)$$

Then Eq. (11) becomes

$$\sum_k w_{\text{Mn}}(\rho_k, z_k) \approx 2n_{\text{Mn}}a_0^3S^2J_{\text{Mn}}\Phi(k_F, \ell) \left[\frac{\langle \psi_a^2 \rangle}{\psi_{\text{max}}^2} \right] \left[\frac{\psi_b^2(h)}{\psi_{\text{max}}^2} \right] \left[\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^2(z)/\psi_{\text{max}}^2] j(z) dz \right]. \quad (13)$$

Substituting (5) and (13) in Eq. (1), one comes to the equation defining the spatial magnetization in the magnetic semiconductor:

$$j(h) = B_S \left[\frac{\mu H(h)}{kT} \right] = B_S \left[\frac{C_{\text{Fe}}(h)}{\tau} + \frac{C_{\text{Mn}}(h)}{\tau} \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^2(z)/\psi_{\text{max}}^2] j(z) dz \right) \right], \quad (14)$$

where $\tau = kT/J_{\text{Mn}}$ is the reduced temperature, $C_{\text{Fe}}(h) = 4\pi n_{\text{Fe}}a_0^3S(J_{\text{Fe}}/J_{\text{Mn}})(\ell_{\text{Fe}}/a_0)^3F(h)$, $C_{\text{Mn}}(h) = C_0 [\psi_b^2(h)/\psi_{\text{max}}^2]$, $C_0 = 2n_{\text{Mn}}a_0^3S^2\Phi(k_F, \ell_{\text{Mn}}) [\langle \psi_a^2 \rangle / \psi_{\text{max}}^2]$.

The solution of that equation is

$$j(h) = B_S \left[\frac{C_{\text{Fe}}(h)}{\tau} + \gamma(\tau)C_{\text{Mn}}(h) \right], \quad (15)$$

where the parameter $\gamma(\tau)$ is defined self-consistently by substituting the function (15) in the relation (14).

Let us consider, firstly, the case $n_{\text{Fe}} = 0$, i.e. the system without the ferromagnetic Fe layer, but with the indirect interaction of magnetic impurities via charge carriers in the quantum well [3]. Then $C_{\text{Fe}}(h) \equiv 0$ and the stated substitution leads to the equation

$$\gamma = \frac{1}{\tau} \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^2(z)/\psi_{\text{max}}^2] B_S [\gamma C_{\text{Mn}}(z)] dz \right), \quad (16)$$

which determines the parameter γ . It has nonzero solution in the low-temperature region $\tau < \tau_C$ only, where τ_C is the Curie temperature.

Near the Curie temperature, the magnetization is low ($j \rightarrow 0$). According to (15) it is possible at $\gamma \rightarrow 0$ only. Using the series $B_S(x) = b_1x - b_3x^3 + \dots$ with $b_1 = (S+1)/3S$, $b_3 > 0$, one finds the solution of Eq. (16)

$$\gamma^2 = \frac{b_1}{b_3 C_0^2} \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^4(z)/\psi_{\text{max}}^4] dz - \frac{\tau}{b_1 C_0} \right) \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^8(z)/\psi_{\text{max}}^8] dz \right)^{-1}, \quad (17)$$

which at $\gamma = 0$ provides the Curie temperature:

$$\tau_C = b_1 C_0 \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^4(z)/\psi_{\text{max}}^4] dz \right) = \tau_0 \left(\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^4(z)/\psi_{\text{max}}^4] dz \right) [\langle \psi_a^2 \rangle / \psi_{\text{max}}^2]. \quad (18)$$

where $\tau_0 = (2/3) n_{\text{Mn}}a_0^3 S(S+1)\Phi(k_F, \ell_{\text{Mn}})$. It determines the temperature range for existing intrinsic (not induced by Fe film) ferromagnetism in Ga(Mn)As.

Assuming now $n_{\text{Fe}} \neq 0$ but $\ell_{\text{Mn}} = 0$, we come to the situation with no indirect interaction of magnetic impurities. In that case, impurities are magnetized due to the exchange interaction with the magnetically ordered system of Fe atoms only. The spatial distribution of such an induced magnetization is defined by Eq. (15), where one should assume $\gamma = 0$. One could estimate the width L_{ind} of that distribution (at the level 1/2) from the condition $B_S[C_{\text{Fe}}(h)/\tau] = 1/2$, which for $S = 5/2$ [15] gives $C_{\text{Fe}}(h)/\tau \approx 1.4$. At $n_{\text{Fe}}a_0^3 \approx 2$, $J_{\text{Fe}}/J_{\text{Mn}} \sim 1$, $\ell_{\text{Fe}} \sim a_0$, $\tau \sim \tau_C$ one finds $L_{\text{ind}} \approx 4\ell_{\text{Fe}}$. Thus, the induced magnetization of Mn atoms exists in a thin layer of the thickness $L_{\text{ind}} \sim 20\text{\AA}$ near the Fe/Mn interface. It is just that layer which serves as a magnetic seed being amplified due to the indirect inter-impurity interaction.

At last, in the general case the spatial distribution of the magnetization is defined by Eq. (15), where the parameter $\gamma(\tau)$ is the root of the equation

$$\frac{1}{a_0} \int_{z=0}^{L_{\text{Mn}}} [\psi_b^2(z)/\psi_{\text{max}}^2] B_S \left[\frac{C_{\text{Fe}}(z)}{\tau} + \gamma(\tau) C_{\text{Mn}}(z) \right] dz - \gamma(\tau) \tau = 0. \quad (19)$$

Formulae (15), (19) is the main result of the present work. To determine the magnetization with the help of those relations, it is necessary to find the wave functions $\psi_a(z)$, $\psi_b(z)$ of charge carriers in different parts of the considered structure.

Such a problem for the heterostructure being the contact of two different semiconductors (e.g., GaAs and GaInAs), one of which (GaAs) is diluted by Mn atoms, has been considered by us early [3]. Opposite in sign charges of ionized impurities and mobile charge carriers in the well produce the electric field \mathcal{E} , which is directed along the normal (z -axis) to the heterojunction plane and makes the potential to be non-uniform: $U = U(z)$. The exact self-consistent determination of the potential $U(z)$ and wave functions of mobile charge carriers requires the consistent solution of Schrödinger and Poisson equations that is usually found by numerical iterative methods [16] (relevant calculations could be performed, for example, by means of the openly accessible package [17]). However, our aim is to derive simple *analytical* expressions describing magnetic properties of the considered system. Thereby, we will use the heterojunction model with the triangle well bottom and barrier top. Tests indicate that wave functions found with that triangle model are very close to exact results [3]. Respective expression for the carrier potential energy has the form

$$U(z) = \begin{cases} U_0 + (z - L_{\text{Mn}})e\mathcal{E}, & z < L_{\text{Mn}}, \\ (z - L_{\text{Mn}})e\mathcal{E}, & z > L_{\text{Mn}} \end{cases} \quad (20)$$

(as previously, $z = L_{\text{Mn}}$ corresponds to the heterojunction plane, magnetic impurities are situated in the region $0 < z < L_{\text{Mn}}$). The slope of the well bottom is determined by the electric field $\mathcal{E} \approx (4\pi/\kappa_0)eN_s$, produced by charges located in the well.

As before, we assume the carrier density being not too high, so that the lowest energy level occurs to be populated only, and the effective width of the well being so small that mixing of light and heavy hole subbands could be neglected. Near the heterojunction ($z = L_{\text{Mn}}$) the wave function of carriers on the lowest energy level E has the form [3]

$$\psi(z) = \mathbb{C} \begin{cases} \psi_b(z) \equiv \text{Ai}[q(z - L_{\text{Mn}}) - \varepsilon/q^2 a_0^2], & z < L_{\text{Mn}} \\ \psi_a(z) \equiv \frac{\text{Ai}(-\varepsilon/q^2 a_0^2)}{\text{Bi}(-\varepsilon/q^2 a_0^2 + u/q^2 a_0^2)} \text{Bi}[q(z - L_{\text{Mn}}) - \varepsilon/q^2 a_0^2 + u/q^2 a_0^2], & z > L_{\text{Mn}} \end{cases}, \quad (21)$$

where $\text{Ai}(z)$, $\text{Bi}(z)$ are Airy functions,

$$u \equiv 2m^*a_0^2U_0/\hbar^2, \quad \varepsilon \equiv 2m^*a_0^2E/\hbar^2, \quad q \equiv \left(\frac{2m^*}{\hbar^2}e\varepsilon\right)^{1/3}, \quad (22)$$

ε is the reduced energy of the populated level in the well defined by the equation

$$\text{Ai}(-\varepsilon/q^2a_0^2)\text{Bi}'(-\varepsilon/q^2a_0^2 + u/q^2a_0^2) - \text{Ai}'(-\varepsilon/q^2a_0^2)\text{Bi}(-\varepsilon/q^2a_0^2 + u/q^2a_0^2) = 0, \quad (23)$$

coefficient C should be found from the normalization condition.

Results

Though above we had to do with the concrete structure Fe–Ga(Mn)As–In(Ga)As, the qualitative character of our consideration makes using accurate values of those parameters that govern its behavior to be excessive. Therefore, we assume $n_{\text{Fe}}a_0^3 = 2$, $n_{\text{Mn}}a_0^3 = 0.15$ (that corresponds to $x \approx 0.1$), $J_{\text{Fe}}/J_{\text{Mn}} = 1$, and for other parameters we suggest typical values $L_{\text{Fe}} = L_{\text{Mn}} = 7a_0$ [1], $\ell_{\text{Fe}} = 0.75a_0$, $\ell_0 = 3a_0$ (that for the bulk diluted magnetic semiconductor Ga(Mn)As corresponds to the hole mobility $\sim 10 \text{ cm}^2/\text{V}\cdot\text{s}$).

The temperature range of existing intrinsic (not induced by Fe film) ferromagnetism in Ga(Mn)As, found for that set of parameters, is bounded from above by a rather low Curie temperature $\tau_C \approx 0.026$ ($T_C \approx 25 \text{ K}$). In Fig. 2, the spatial distribution $j_{\text{Mn}}(z)$ of the intrinsic local magnetization of Mn atoms is shown for the temperature τ , close the critical one (the curve $\text{Mn} \leftrightarrow \text{Mn}$). In the same figure, spatial distributions of Mn magnetization, induced by the exchange interaction with Fe atoms and decaying with moving off the interface Fe/Ga(Mn)As ($z = 0$), are represented (curves $\text{Fe} \leftrightarrow \text{Mn}$) for the case when their indirect interaction is switched off. At last, curves ($\text{Fe} \leftrightarrow \text{Mn} + \text{Mn} \leftrightarrow \text{Mn}$) are the result of the combined action of the two magnetic ordering mechanisms revealing good shows of the induced ferromagnetism amplification due to the indirect interaction of magnetic Mn impurities. Remarkably, significant amplification of the induced magnetization keeps at temperatures which are higher than the Curie temperature corresponding to the intrinsic ferromagnetism of Ga(Mn)As.

Magnetization $j_{\text{Mn}}(z = L_{\text{Mn}})$ near the heterojunction plane is of special interest because it is just this value determines the spin polarization degree of charge carriers in two-dimensional conductivity channel. Let N_s^- , N_s^+ be concentrations of two-dimensional holes with spins antiparallel and parallel to the magnetization, respectively. Then, the spin polarization degree $\xi = (N_s^- - N_s^+)/N_s$ ($N_s = N_s^- + N_s^+$ is their total concentration) of holes is defined by the effective magnetic spin-dependent potential which for the bulk diluted magnetic semiconductor with the uniform magnetization j_{Mn} has the form $V_{\text{mag}} = n_{\text{Mn}}a_0^3J_{pd}\sigma S_{\text{Mn}}j_{\text{Mn}}$ [18], where $\sigma = \pm 1/2$ is the hole spin. In the considered case, when charge carriers and magnetized Mn atoms are spatially separated, that relation should be added by the factor allowing for the fact that their interaction occurs through the tail of the carrier wave function which, additionally, is non-uniform within the channel region:

$$\langle V_{\text{mag}} \rangle = j_{\text{Mn}}(L_{\text{Mn}}) n_{\text{Mn}}a_0^3J_{pd}\sigma S_{\text{Mn}} \cdot [\psi_a^2(L_{\text{Mn}})/\langle \psi_a^2 \rangle]. \quad (24)$$

The magnetic potential (24) leads to splitting the energy level E in two spin sub-levels with energies $E^+ = E + V_{\text{mag}}$ and $E^- = E - V_{\text{mag}}$. Concentrations of two-dimensional carriers at each of them are defined by relations $N_s^\pm \propto E^\pm$, wherefrom it follows

$$\xi = 2\langle V_{\text{mag}} \rangle/E = j_{\text{Mn}}(L_{\text{Mn}}) \cdot \xi_0, \quad (25)$$

where $\xi_0 = 2n_{\text{Mn}}a_0^3\sigma S_{\text{Mn}}(J_{pd}/E)[\psi_a^2(L_{\text{Mn}})/\langle\psi_a^2\rangle]$. In the considered system $\xi_0 \sim 0.5$, so that $\xi \sim j_{\text{Mn}}(L_{\text{Mn}})$. The amplification of the magnetization in the region adjoining the heterojunction results in the proportionate increasing of the spin polarization of charge carriers in the two-dimensional channel.

Fig. 3 demonstrates temperature dependencies of the magnetization of Mn atoms near the heterojunction plane: the lower curve ($\text{Fe} \leftrightarrow \text{Mn}$) shows the induced magnetization, the upper curve ($\text{Fe} \leftrightarrow \text{Mn} + \text{Mn} \leftrightarrow \text{Mn}$) – the induced one, amplifying by the indirect interaction. The latter corresponds also (on a certain scale) to the temperature dependence of the spin polarization in the hole channel. Evident magnetization $j_{\text{Mn}}(L_{\text{Mn}})$ ($\sim 10\%$) remains up to temperatures $\tau \sim 20\tau_C \sim 0.5$, that corresponds to $T \sim 500$ K.

In the insert, the temperature dependence of the respective amplification factor K_j , equal to the ratio of the two mentioned magnetizations, is shown. The maximum amplification occurs at $\tau \gg \tau_C$ and comes about $K_j \approx 1.6$. Though this effect, as such, could be important, but the most interesting feature of the considered structure is the significant mobility increasing of spin-polarized charge carriers (in two-dimensional conductivity channel): in comparison with the mobility in the bulk Ga(Mn)As, it increases according to (10) by $\ell_{\text{Mn}}/\ell_0 \approx 25$ times and reaches the value $\mu_h \sim 10^3$ cm²/V·s for the accepted parameters' set.

Conclusions

Magnetic properties of the planar structure Fe–Ga(Mn)As–In(Ga)As, which consists of the diluted magnetic semiconductor bordering upon the ferromagnetic metal (on one side) and upon the quantum well (on another side), are considered. In the framework of the mean-field theory, there has been demonstrated the significant amplification of the magnetization, induced by the ferromagnetic metal, in the semiconductor region close to the interface due to the indirect interaction of magnetic impurities via the conductivity channel. Existing evident high-temperature magnetization in the considered structure (and, hence, the noticeable spin polarization of carriers, too) is provided by the interaction of Mn atoms with Fe film (keeping magnetization up to ~ 1000 K), and the high mobility of spin-polarized charge carriers – by their moving from the charged impurities. Such a favorable combination of the two important parameters in the considered structures holds out a hope that they could be of interest as possible elements of different spintronic devices.

References

- [1] F. Maccerozzi, M. Sperl, G. Pannacione, J. Minár, S. Polesya, H. Ebert, U. Wurstbauer, M. Hochstrasser, G. Rossi, G. Woltersdorf, W. Wegs Schneider, C.H. Back, Phys. Rev. Lett., **101**, 267201 (2008).
- [2] E.Z. Meilikhov, R.M. Farzettinova, Phys. Lett. A, **373**, 2770 (2009).
- [3] E.Z. Meilikhov, R.M. Farzettinova, JETP Letters, **87**, 482 (2008); JETP, May 2010 (in print).
- [4] R. Moriya, H. Munekata, J. Appl. Phys., **93**, 4603. (2003).
- [5] M.A. Pankov, B.A. Aronzon, V.V. Rylkov, A.B. Davidov, E.Z. Meilikhov, R.M. Farzettinova, E.M. Pashaev, M.A. Chuev, I.A. Subbotin, I.A. Likhachev, B.N. Zvonkov, A.V. Lashkul, R. Laiho, JETP, **109**, 274 (2009).
- [6] A.M. Nazmul, T. Amemiya, Y. Shuto, S. Sugahara, and M. Tanaka , Phys. Rev. Lett., **95**, 017201 (2005).
- [7] T. Dietl, H. Ohno, F. Matsukara, J. Cibert, and D. Ferrand, Science, **287**, 1019 (2000).
- [8] T. Jungwirth, Jairo Sinova, J. Mašek, J. Kucéra, A. H. MacDonald, Rev. Mod. Phys. **78**, 809 (2006).
- [9] P.M. Krstajic, V.A. Ivanov, F.M. Peeters, V. Fleurov, and K. Kikoin, Europhys. Lett., **61**, 235 (2003).
- [10] N. Bloembergen, and T.J. Rowland, Phys. Rev., **97**, 1679 (1955).
- [11] V.I. Litvinov, and V.K. Dugaev, Phys. Rev. Lett., **86**, 5593 (2001).
- [12] D. N. Aristov, Phys. Rev. B. 55, 8064 (1997).
- [13] D.J. Priour, Jr., E.H. Hwang, and S. Das Sarma, Phys. Rev. Lett., **95**, 037201 (2005).
- [14] P.G. de Gennes, J. Phys. Radium, **23**, 630 (1962).
- [15] T.C. Schulthess, W.M. Temmerman, Z. Szotek, A. Svane, L. Petit, J. Phys.: Condens. Matter, **19**, 165207 (2007).
- [16] T. Ando, A. Fowler, and F. Stern, Rev. Mod. Phys., **54**, No. 2 (1984).
- [17] <http://www.nextnano.de/>; <http://www.nd.edu/gsnider/>.
- [18] M.A. Boselli, I.C. da Cunha Lima, A. Ghazali, Phys.Rev. B, **68**, 085319 (2003).

Figure captions

Fig. 1. Heterostructure $\text{Fe}-\text{Ga}_{1-x}\text{Mn}_x\text{As}-\text{In}_y\text{Ga}_{1-y}\text{As}$. 2D – quasi-two-dimensional conductivity channel in the quantum well.

Fig. 2. Spatial distributions of Mn atoms' magnetization. $(\text{Fe} \leftrightarrow \text{Mn})$ – induced magnetization, $(\text{Fe} \leftrightarrow \text{Mn} + \text{Mn} \leftrightarrow \text{Mn})$ – induced magnetization amplified by the indirect interaction, $(\text{Mn} \leftrightarrow \text{Mn})$ – intrinsic magnetization. Structure parameters: $u = 0.36$, $qa_0 = 0.25$, $k_F a_0 = 0.1$, $L_{\text{Fe}} = L_{\text{Mn}} = 7a_0$, $\ell_0 = 3a_0$, $n_{\text{Fe}} a_0^3 = 2$, $n_{\text{Mn}} a_0^3 = 0.15$, $\ell_{\text{Fe}} = 0.75a_0$, $J_{\text{Fe}}/J_{\text{Mn}} = 1$.

Fig. 3. Temperature dependencies of Mn atoms' magnetization near the heterojunction plane: $(\text{Fe} \leftrightarrow \text{Mn})$ – induced magnetization, $(\text{Fe} \leftrightarrow \text{Mn} + \text{Mn} \leftrightarrow \text{Mn})$ – induced magnetization amplified by the indirect interaction. Structure parameters are the same as in Fig. 2. In the inset: temperature dependence of the amplification factor.





